

Stirling engine based solar-thermal power plant with a thermo-chemical storage system



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ABSTRACT

This paper describes a solar-thermal run Stirling engine based uninterrupted power generating system employing magnesium sulphate impregnated Zeolite pellets for thermal energy storage. In the proposed system, Stirling engine design is based on the average temperature difference of 480 °C, assuming the heat sink temperature equal to the ambient temperature of that place. In presence of sun, Fresnel lenses of a specially designed hybrid capsule capture solar energy and concentrate them to provide necessary heat for the operation of the engine. In absence of the sun, required heat is provided by the thermo-chemical energy stored in Zeolite pellets. Working methodologies, modelling and simulation of the proposed system along with analyses of the obtained simulated results are presented in this paper. Possible performance of the scheme at different global positions for different period of a year has also been investigated.

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1. Introduction

Electricity has become the fundamental necessity of modern world. More than 80% of electrical power is generated from fossil fuels [1]. The fixed reserve and the harmful effects of these conventional fuels have compelled researchers to think of alternatives. Scientists consider renewable energy resources as the best substitute of the trendy energy sources [2,3]. Amongst all the inexhaustible resources, solar energy is most abundant in terms of generating capability and a lot of work has been done to explore its potential on earth [4–7]. Most of the work, on solar energy for electricity generation, is based on photovoltaic (PV) with battery storage [2,8–11]. This paper presents a method of solar-thermal power generating system with thermo-chemical storage (magnesium sulphate impregnated Zeolite pellet). The thermo-chemical storage alleviates most of the shortcomings of traditional battery storage system like heavy weight, fixed life span, more charging time than discharging time, etc. In the proposed scheme, solar tracking system, which is an indispensable part of a PV technology, is replaced by a hybrid capsule consisting of glass and Fresnel lens reducing the complexity and additional energy consumption thereby decreasing expenses.

Stirling engine is the heart of the plant that converts the thermal energy in solar irradiance into mechanical energy. Stirling

engine is an external combustion engine developed by Dr. Robert Stirling in 1816 [12,13]. It is a closed-cycle regenerative machine that operates on cyclic compression and expansion of the working fluid [13]. Stirling engine has higher thermal efficiency than Rankine cycle based system and is reported that it is cheaper than PV unit of small capacity [14]. Some other advantages of Stirling engine are multi-fuel capability, low noise, low fuel consumption, capability of using various fuel sources, etc. [15]. Due to the pronounced merits of Stirling engine, many researchers have shown interest in it. Can et al. [16] developed a Beta type Stirling engine using crank mechanism while, Aksoy and Cinar [17] performed theoretical investigation on kinematic and thermodynamic analysis of a beta type Stirling engine with rhombic-drive mechanism. Abbas et al. worked with dish Stirling technology with hydrogen as working fluid [18], on the other hand, Moghadam et al. [19] proposed a solar dish micro-combined heat and power (CHP) system and carried out its 3E (energy, environment and economic) based analysis. In [20], a delta-T Stirling engine have been developed and experimented by Boutammachte et al. under laboratory and field condition, conversely, an unconventional liquid piston Stirling engine pump was proposed by Van de Ven in [21] which was supposed to closely match the ideal engine cycle. Solmaz and Karabulut [22] explored the performance of a Stirling engine with a lever controlled displacer driving mechanism by comparing it with a rhombic-drive engine whereas, Karabulut et al. [23] carried out an experimental test on a similar system and presented the results. In the system, heat was supplied by liquefied petroleum gas (LPG) burner. The maximum power of 183 W was achieved with hot end

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Nomenclature

a	Stirling engine constant	v	ratio of swept volume of compression and swept volume of expansion
AM	air mass	V_{dc}	dead volume of compression space (cm ³)
b	Stirling engine constant	V_{de}	dead volume of expansion space (cm ³)
c	Stirling engine constant	V_r	regenerator volume (cm ³)
d	day of the year	V_{sc}	swept volume of compression space (cm ³)
D_x	phase angle (°)	V_{se}	swept volume of expansion space (cm ³)
EoT	equation of time (min)	W_c	rejected thermal energy from the engine to environment (J)
HRA	hour angle (°)	W_e	indicated expansion energy i.e. input thermal energy from sun to the engine
I_s	solar irradiance (W/m ²)	W_i	indicated energy (J)
L_a	total area of Fresnel lenses (m ²)	x	crank angle variation (°)
LT	local time	X_{dc}	ratio of dead volume of compression and swept volume of expansion
LST	local solar time	X_{de}	ratio of dead volume of expansion and swept volume of expansion
$LSTM$	local standard time meridian	X_r	ratio of regenerator volume and swept volume of expansion
M_g	mass of working gas (g)	z	time (s)
n	engine speed (r.p.m)	α	elevation of sun (°)
P_e	engine pressure (kPa)	δ	declination angle (°)
P_m	mean pressure (kPa)	ϕ	latitude (°)
P_o	output power of engine in one complete cycle (W)	θ	zenith angle (°)
R	working fluid constant (gas constant) (J/kg K)		
s	Stirling engine constant		
t	ratio of compression temperature and expansion temperature		
TC	time correction factor (min)		
T_c	fluid temperature of compression (°C)		
T_e	fluid temperature of expansion (°C)		

temperature of 260 °C and cold end temperature of 27 °C at speed of 600 rpm.

In the context of contemporary studies, the proposed scheme (depicted in Section 2) in the paper with some assumptions (Table 1) establishes a steady power output in diverse situations.

Stirling engine is driven by external heat and hence anything that can store thermal energy like water, rocks, concrete, pebbles, etc., can be used as backup source of heat for its operation. Amongst all the thermal storage system, chemical heat storage has the highest potential for long term storage [24]. Heat storage in the form of sensible and latent heat is the most studied technologies and is at an advanced state of development [25]. Thermal energy is stored in sensible heat storage by raising the temperature

of the material. The storage density is then equal to the product of the specific heat of the material and the temperature change. On the other hand, Latent heat is the quantity of heat absorbed or released by a material, while changing its phase at a constant temperature. A phase change material (PCM) melts and takes up energy corresponding to the latent heat of the material when the temperature increases above the melting point. Conversely, the latent heat is released when the material is cooled back and the PCM solidifies. But sensible heat storage material and PCM progressively lose heat and are not suitable for long term storage which is undesirable especially for polar region [25]. Materials used for sorption storage have the highest storage density and some have even storage density near to that of Biomass [25]. Zeolites are alumina silicates that are considered to be most suitable for accumulation of heat by water adsorption–desorption process [26]. Natural Zeolites has lower performance compared to their synthetic counter parts [27]. Synthetic Zeolite has larger pore size, higher specific surface area [28] and higher operating temperature [26,28] with higher experimental energy storage density (124 kW h/m³) [25]. Zeolites have proved to be a favourable porous expanded structure for magnesium sulphate (MgSO₄) with energy densities of 150–400 kW h/m³ at a storage temperature compatible with solar-thermal collectors [24]. Whiting et al. [29], reported that impregnation of Zeolite Na–Y composite containing 15 wt% of MgSO₄ achieved highest heat of hydration (1090 J g^{−1}). MgSO₄ with water (H₂O) has energy density of 2.8 GJ/m³ [24] and hence, MgSO₄ impregnated Zeolite pellet bed is considered as storage system for the plant.

2. Methodology and description of the system

The block diagram of the plant is shown in Fig. 1.

The operation of the plant can be divided into three stages: Solar energy reception and concentration, conversion of thermal energy into mechanical energy and storage and release of solar-thermal energy.

Table 1
Assumptions made for system simulation.

Parameters	Assumptions
Hemisphere of the earth	Northern hemisphere
Longitude	92°E (fixed)
I_s	Depends on co-ordinates of the place and season
L_a	3 m ²
Rated capacity of Stirling engine	1.3 kW
Working fluid	Air
R	287 J/kg K
T_e	500 °C
T_c	Ambient temperature of the place
n	1500
x	0–360°
D_x	90°
V_r	0.2 cm ³
V_{se}	500 cm ³
V_{sc}	500 cm ³
V_{de}	0.2 cm ³
V_{dc}	0.2 cm ³
Storage system	MgSO ₄ impregnated Zeolite pellet bed
Temperature of thermal energy released by storage system	500 °C
Efficiency of the alternator	80%

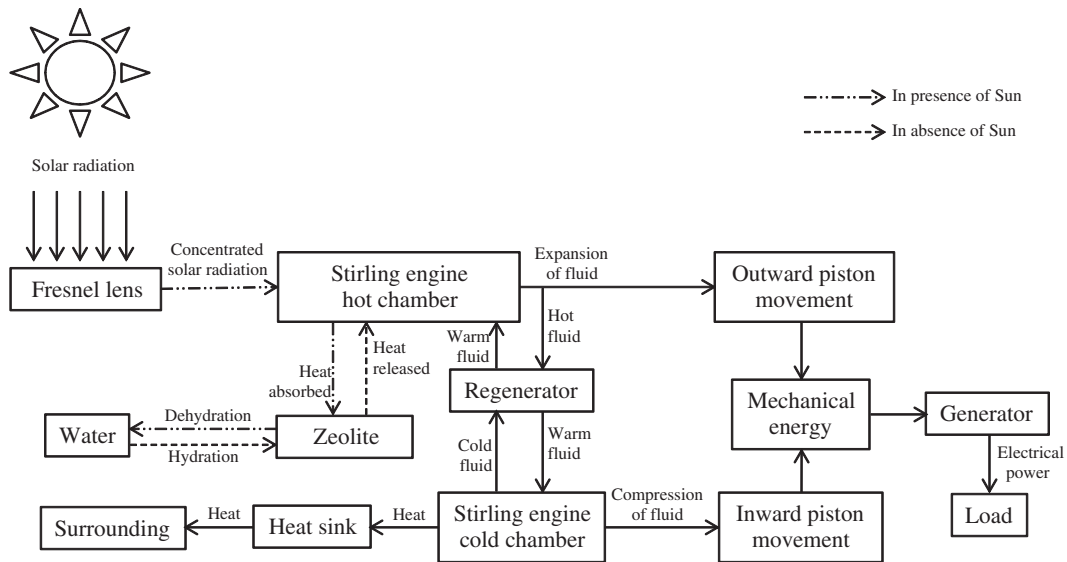


Fig. 1. Block diagram of the plant.

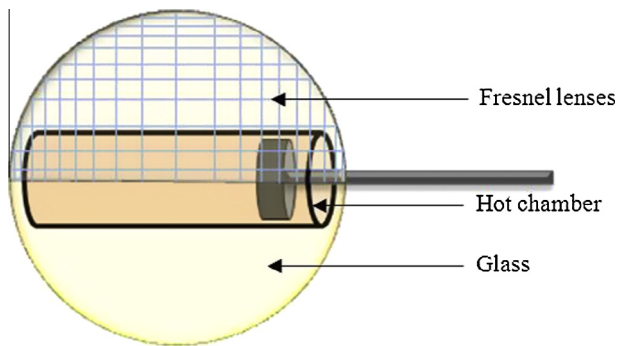


Fig. 2. Hybrid capsule.

engine, captures the solar radiation and concentrates them on it. The upper part of the capsule is a hemisphere made up of a number of Fresnel lenses which does the operation of concentration and lower half is a hemisphere made up of glass and hence, the complete capsule is called 'hybrid'. Temperature of the concentrated radiation depends on the area of focal point and decreases with distance away from it. Thus, temperature of the hot chamber can be kept constant by varying size of the used lenses or varying focal point area or varying the distance of the related lenses from it. The three dimensional view of the capsule along with hot chamber is shown in Fig. 2.

Due to the hemispherical shape of the upper half, hot chamber of the engine gets perpendicular concentrated solar radiation at every position of the sun. Thus the necessity of a solar tracking system is eliminated.

2.1. Stage 1

The process of power generation starts with sun rise. A specially designed hybrid capsule, housing the hot chamber of Stirling

2.2. Stage 2

In the second stage, a Stirling engine converts the thermal energy present in concentrated solar radiation into mechanical

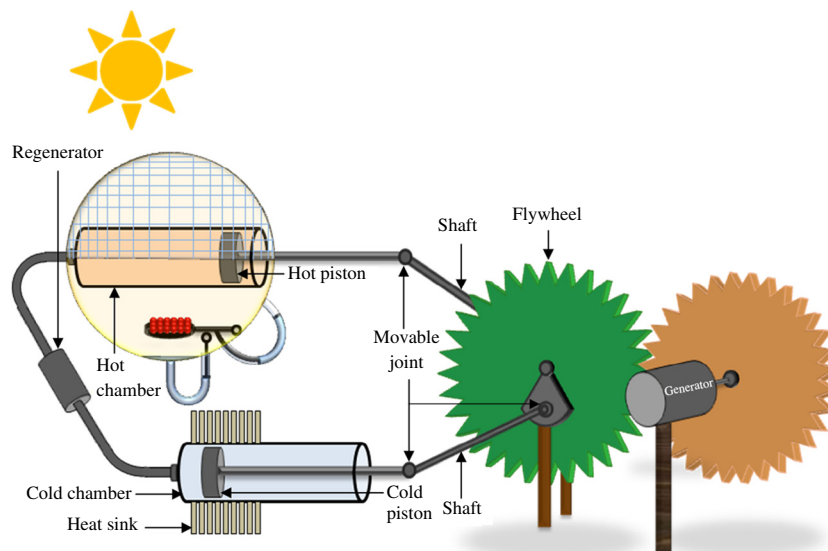


Fig. 3. Three dimensional view of the complete plant.

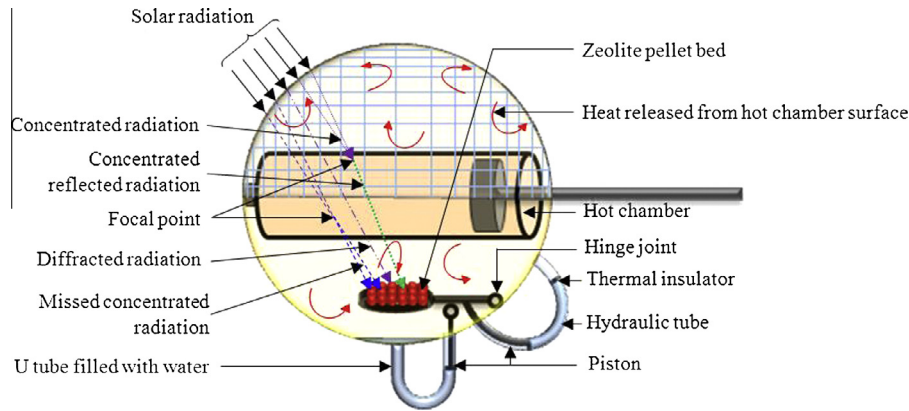


Fig. 4. Storage process.

Table 2
Mathematical equations of Stirling engine.

Equations
$t = \frac{r}{l_e}$
$v = \frac{V_{se}}{V_{se}}$
$X_{de} = \frac{V_{se}}{V_{se}}$
$X_{dc} = \frac{V_{se}}{V_{se}}$
$X_r = \frac{V_{se}}{V_{se}}$
$a = \tan^{-1} \frac{v \sin D_x}{t + \cos D_x}$
$b = \sqrt{t^2 + 2v \cos D_x + v^2}$
$s = t + 2tX_{de} + \frac{4tX_r}{1+t} + v + 2X_{dc}$
$c = \frac{b}{s}$
$W_e = (I_s \times L_a \times z)$
$P_m = \frac{W_e(1 + \sqrt{1 - c^2})}{V_{se} \pi c \sin a}$
$M_g = \frac{P_m(V_{se} \sqrt{s^2 - b^2})}{2RT_c}$
$P_e = \frac{P_m \sqrt{1 - c^2}}{1 - c[\cos(x - a)]}$
$W_i = W_e + W_c$
$P_0 = \frac{n \times W_i}{60}$

energy. This mechanical power is used to drive a generator to generate electrical power. In absence of sun, required heat for the operation of the engine is supplied by a bed of MgSO_4 impregnated Zeolite pellet. An alpha type Stirling engine has been selected here to act as a prime mover for the generator. The three dimensional view of the complete system is shown in Fig. 3.

2.2.1. Operation of the engine

The material of the hot chamber absorbs the heat available from concentrated radiations and transfers it to the fluid inside it. This produces an expansion of the fluid which pushes the piston outward rotating the flywheel. The expanded hot fluid passes through regenerator to the cold chamber. The regenerator absorbs some of the heat from the fluid during its passage from the hot chamber to cold chamber and thus pre-cools it. The cold chamber is surrounded by heat sink which absorbs the heat from the fluid making it cool and produces a compression. Hence, the piston in the cold chamber is sucked inside. This suction enhances the rotation of the flywheel. Due to inertia of the flywheel, it rotates more than it would have just for suction only. This extra movement pushes the piston in the cold chamber and pulls the piston in the hot chamber. Consequently, the cold fluid moves from cold chamber to the hot chamber through the regenerator. The regenerator absorbs the cold and releases the heat absorbed in previous passage, and thus pre-heats the fluid. This cycle continues till there is remarkable temperature difference between the two chambers.

Table 3
Equations for simulation of solar irradiance.

Equations
$B = \frac{360}{365} (d - 81)$
$EoT = 9.87 \sin(2B) - 7.53 \cos(B) - 1.5 \sin(B)$
$LSTM = 15^\circ \cdot \Delta T_{GMT}$
$TC = 4(\text{Longitude} - LSTM) + EoT$
$LST = LT + \frac{TC}{60}$
$HRA = 15^\circ(LST - 12)$
$\delta = 23.45^\circ \sin(B)$
$\alpha = \sin^{-1}[\sin \delta \sin \phi + \cos \delta \cos \phi \cos(HRA)]$
$\theta = 90^\circ - \alpha$
$AM = \frac{1}{\cos \theta}$
$I_s = 1.353 \times 0.7^{(AM^{0.678})}$
$Sunrise = 12 - \frac{1}{15} \cos^{-1} \left(\frac{-\sin \phi \sin \delta}{\cos \phi \cos \delta} \right) - \frac{TC}{60}$
$Sunset = 12 - \frac{1}{15} \cos^{-1} \left(\frac{-\sin \phi \sin \delta}{\cos \phi \cos \delta} \right) - \frac{TC}{60}$

As a result, there is a to and fro motion of the pistons which keeps the flywheel in continuous motion. The flywheel is coupled to the shaft of the generator which gets rotated and as a result, electrical power is generated.

2.3. Stage 3

Zeolite pellets have the property of storing thermal energy when they are dehydrated by any means of heat. In the proposed scheme, thermal energy of sun is employed to heat the hot chamber. The heat released from the external surface of hot chamber, reflected and diffracted rays from chamber and concentrated rays missing the chamber dehydrates the Zeolite pellet bed and get stored in their chemical bonding. The storage system is shown separately in Fig. 4 to comprehend the system description clearly.

The Zeolite pellet bed is hinged inside the glass envelop so that it can move around the hinge. There are two tubes named U tube and hydraulic tube which are fixed externally to the capsule to open inside it. Each tube has a piston inside them which are pivoted to the Zeolite pellet bed. The hydraulic tube has a thermal insulator at one end and the piston on the other end with water in between. Zeolite bed is fixed to the shaft of this piston so as to move along with it. This tube operates as a hydraulic pump and hence it is named so. The U tube has piston in one end and rest is filled with water.

When the air inside the capsule expands due to accumulation of heat, it pushes the thermal insulator inside the hydraulic tube. As a result, piston of this tube experiences a push and consequently lifts the Zeolite bed above the water level. As the piston of U tube is

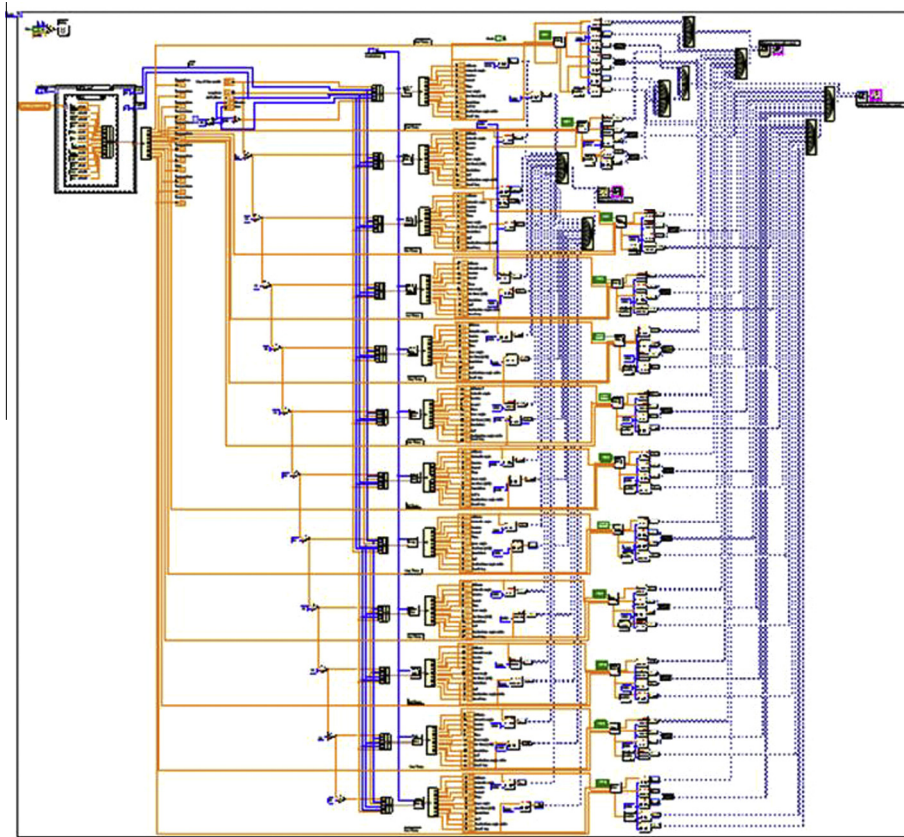


Fig. 5. LabVIEW block diagram of the plant for monthly results.

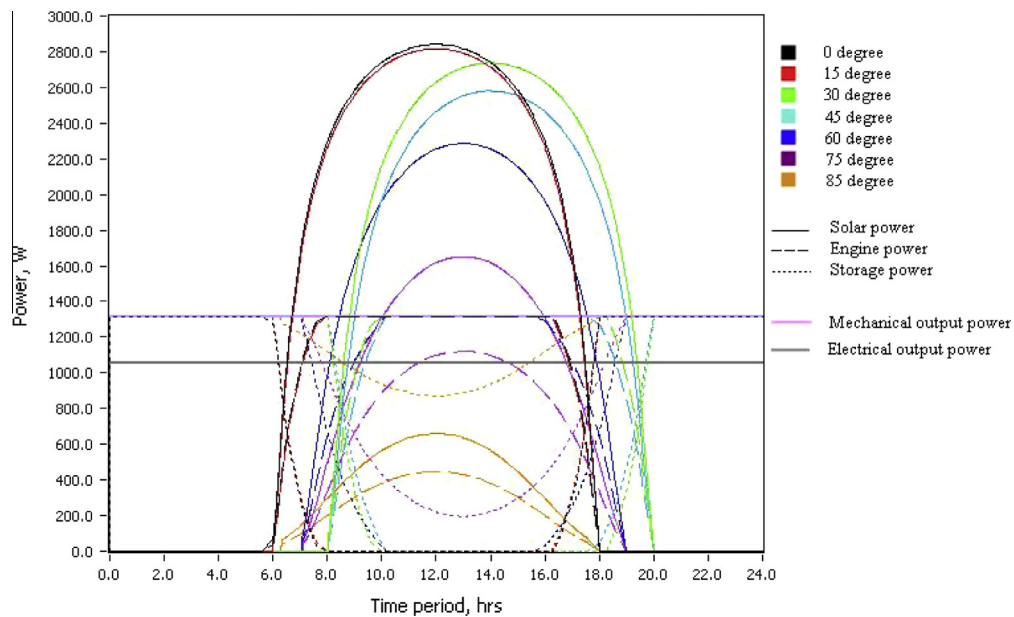


Fig. 6a. Spring equinox.

attached to the Zeolite bed, suction is created in the tube which sucks the water from the capsule inside it.

At night when there is no sun or there is a drop in pressure inside the capsule due to reduction in heat, the Zeolite bed comes down due to gravitational force. The piston in U tube pushes out the water in the tube into the capsule. When this water comes in contact with the Zeolite bed, entrapped energy in it gets released.

At the same time, piston of hydraulic tube pushes water and ultimately the thermal insulator reaches its initial position.

3. Assumptions and system modelling

Stirling engine has been modelled according to Schmidt theory as it is considered to be the simplest and useful method for

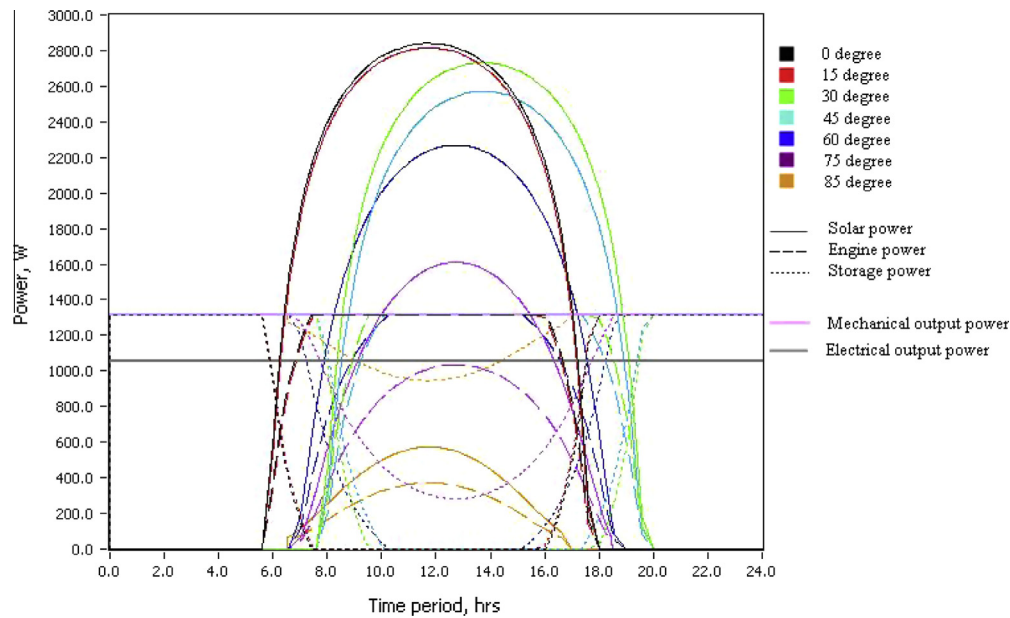


Fig. 6b. Autumnal equinox.

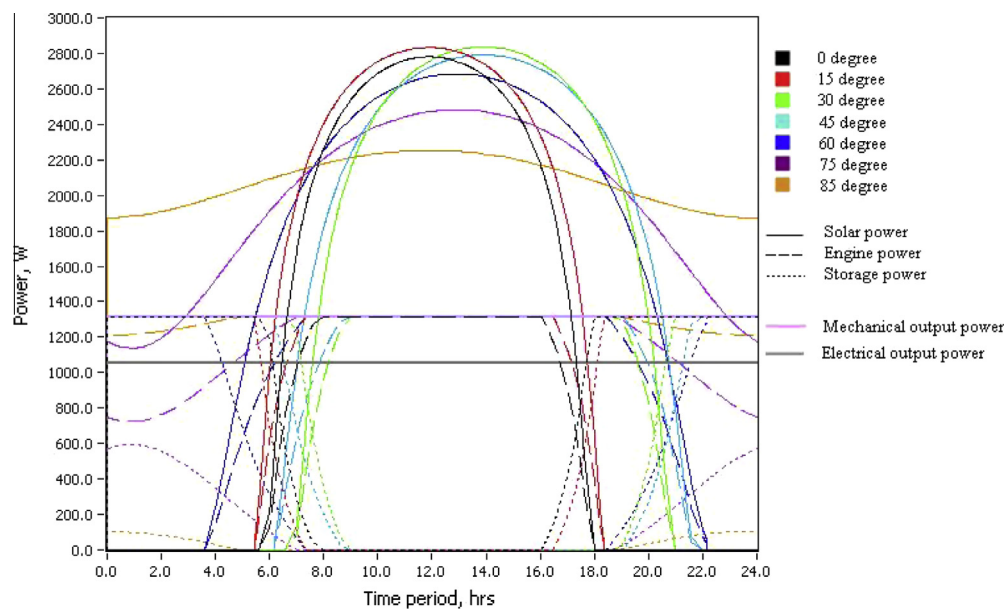


Fig. 6c. Summer solstice.

modelling the Stirling engines [30]. This theory is based on the isothermal expansion and compression of an ideal gas. Different assumptions for modelling the plant are shown in Table 1.

Important equations for modelling Stirling engine are given in Table 2.

The thermo-chemical storage working pair is magnesium sulphate (MgSO_4) and water (H_2O). Heat is released or stored by the hydration or dehydration of magnesium sulphate by the following reaction [29]:



4. Possible performance of the plant at different latitudes

Solar radiation incident on the Earth's atmosphere is relatively constant, but radiation at the Earth's surface varies widely. Global solar intensity is almost uniform throughout the year in

equatorial belt (latitude 0° – 15°). It also has high atmospheric humidity and hence, it is moderately favourable for solar power generation. The belt of latitude extending from 15° to 30° receives more than 90% of the incident solar radiation as direct radiation and has sunshine over 3000 h per year making it most suitable site for solar generation. The latitude belt of 30° – 45° is less favourable for generation from solar energy as scattering of the solar radiation is significant because of the higher latitudes and lower solar altitude. The prospect of solar energy generation declines beyond 45° of latitude due to lack of direct solar radiation. The proposed system is designed to operate in all climatic conditions with varying solar receptions. Thus, to assess its performance in different climatic condition and solar radiation receptions, latitude with 15° interval has been chosen. Latitudes have been varied linearly along longitude of 92°E due to availability of Greenwich Mean Time (GMT) offset of all the latitude.

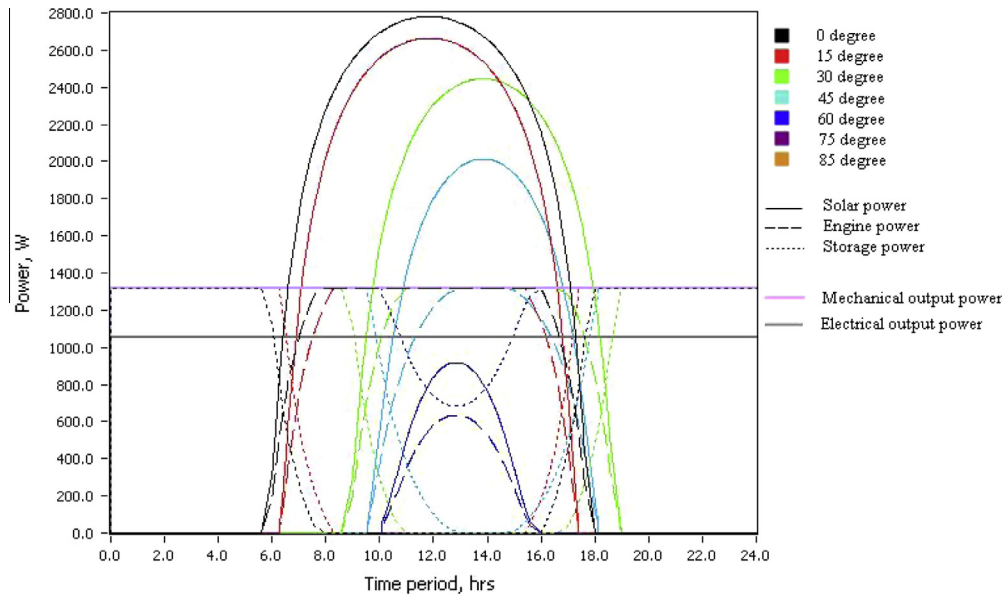


Fig. 6d. Winter solstice.

Due to unavailability of measured data at different latitude, a prediction model for simulating solar irradiance has been developed. The modelling equations are presented in Table 3.

The application of the proposed technique for power generation with Stirling engine aided solar-thermal with thermo-chemical storage arrangement has not been explored yet. Before installing a solar energy system, it is necessary to examine its performance under likely solar energy available for a site. Solar radiation is unevenly distributed throughout the world because of varying solar altitude which is associated with latitude, season and atmospheric conditions. Thus, simulation is the best way to predict the operation and check the feasibility of the practical system in various locations in different solar potential.

So, likely annual power yield of the plant at places having longitude of 92°E and latitude of 0°N, 15°N, 30°N, 45°N, 60°N, 75°N and 85°N has been analyzed in LabVIEW 8.6. Required temperature data for performance simulation of the system has been used from NASA's surface solar energy data set [31]. The LabVIEW block diagram presenting the monthly results is shown in Fig. 5.

4.1. Daily power yield of the plant at different latitude

Earth completes its revolution around the sun in an elliptical path in 365 days and 6 h. During its trip, it passes through four extreme positions: spring (or vernal) equinox, autumnal (or fall) equinox, summer solstice and winter solstice occurring on or about

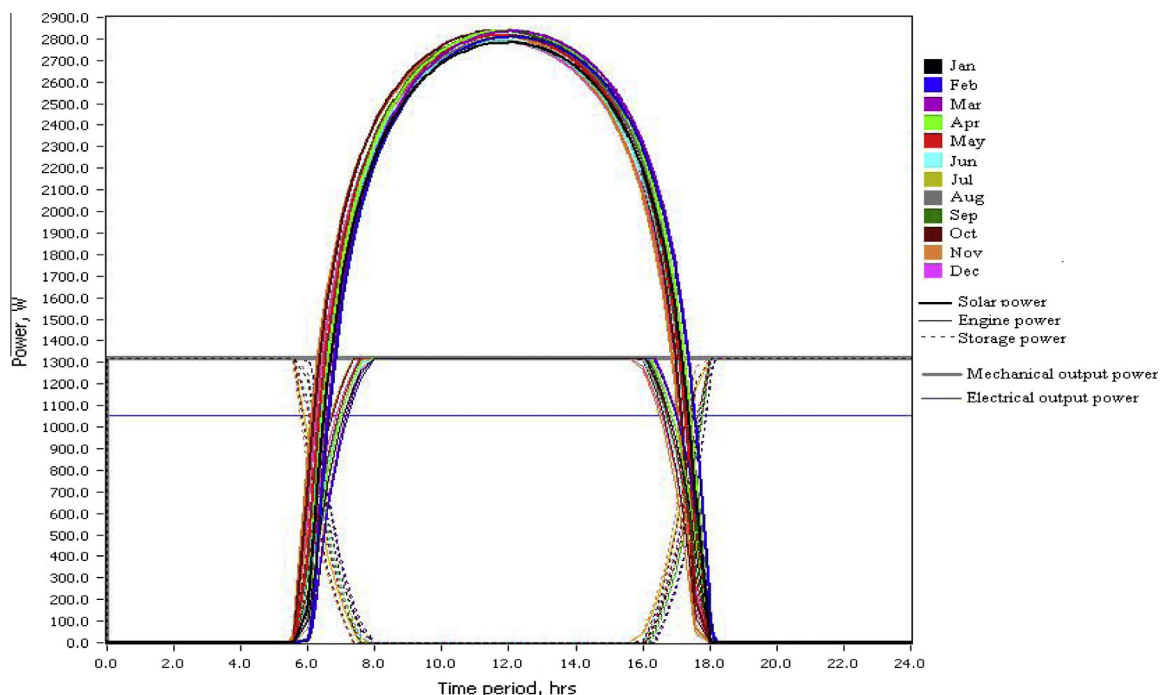


Fig. 7a. At 0° latitude.

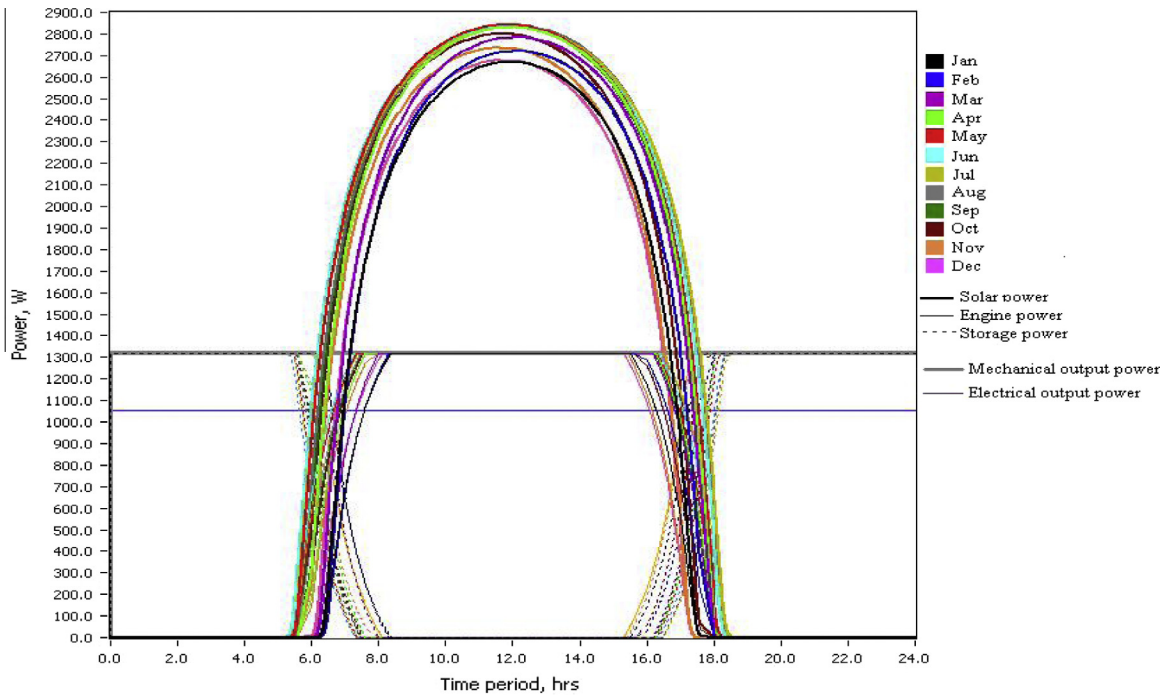


Fig. 7b. At 15° latitude.

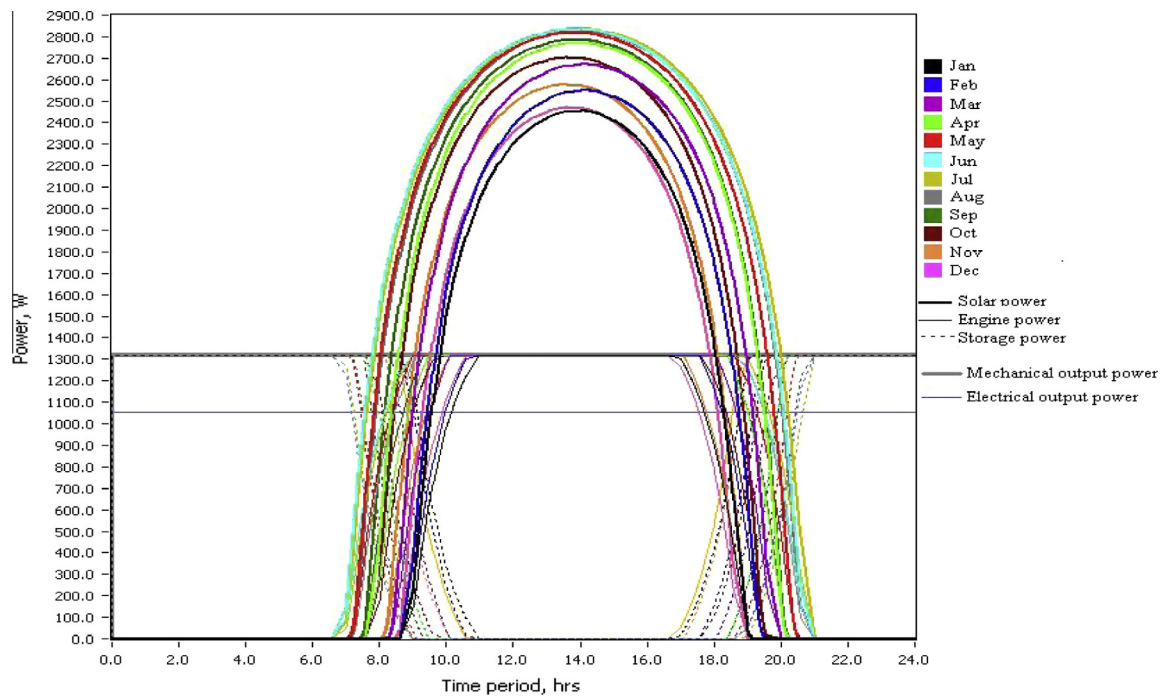


Fig. 7c. At 30° latitude.

20th March (80th day), 22 September (266th day), 21 June (173rd day) and 21 December (355th day) respectively.

During revolution of earth, its axis gets oriented perpendicular to the sun's rays twice a year on the spring equinox and the autumnal equinox. On these days, exactly half of both the northern and southern hemisphere (except the pole) receives just about 12 h of daylight. From the perspective of a surface observer located anywhere except the poles, the sun rises exactly in the east and sets

precisely in the west. Furthermore, at the Equator, the sun appears directly overhead at local noon.

At north pole, the spring equinox marks the beginning in the increment of sunshine duration towards 24 h of daylight and vice versa from the autumnal equinox.

Twice a year, there is a maximal inclination of earth's axis towards and away from the sun called solstices (summer and winter solstice). On summer solstice, the north pole axis tilts 23.5°

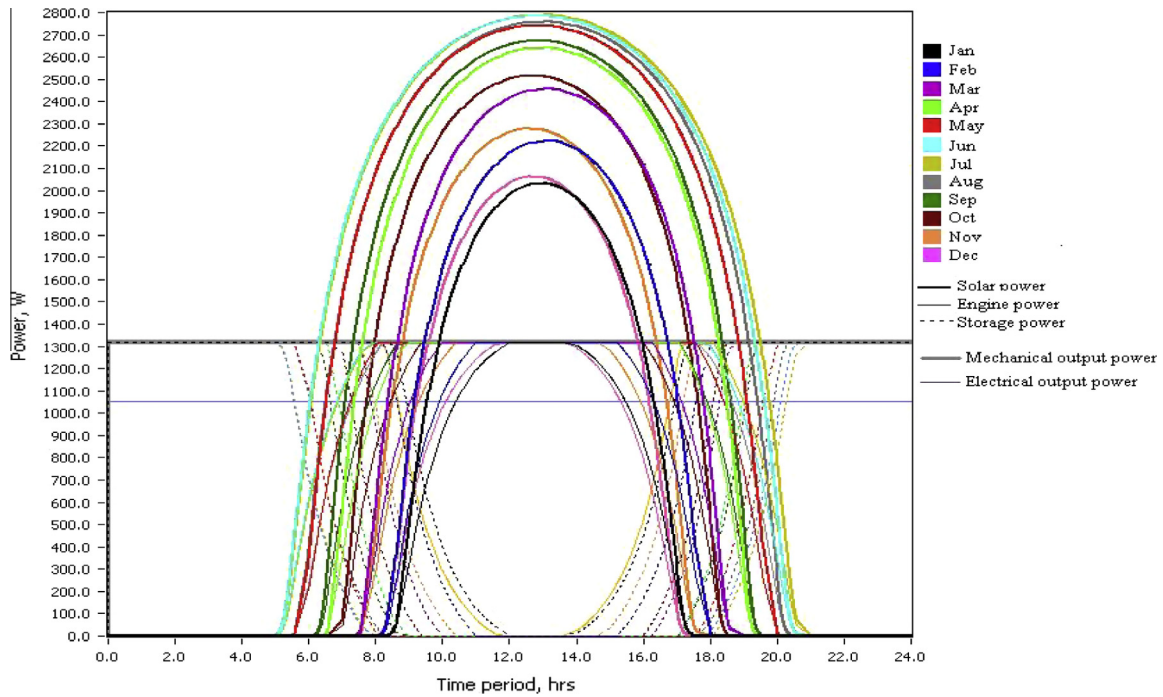


Fig. 7d. At 45° latitude.

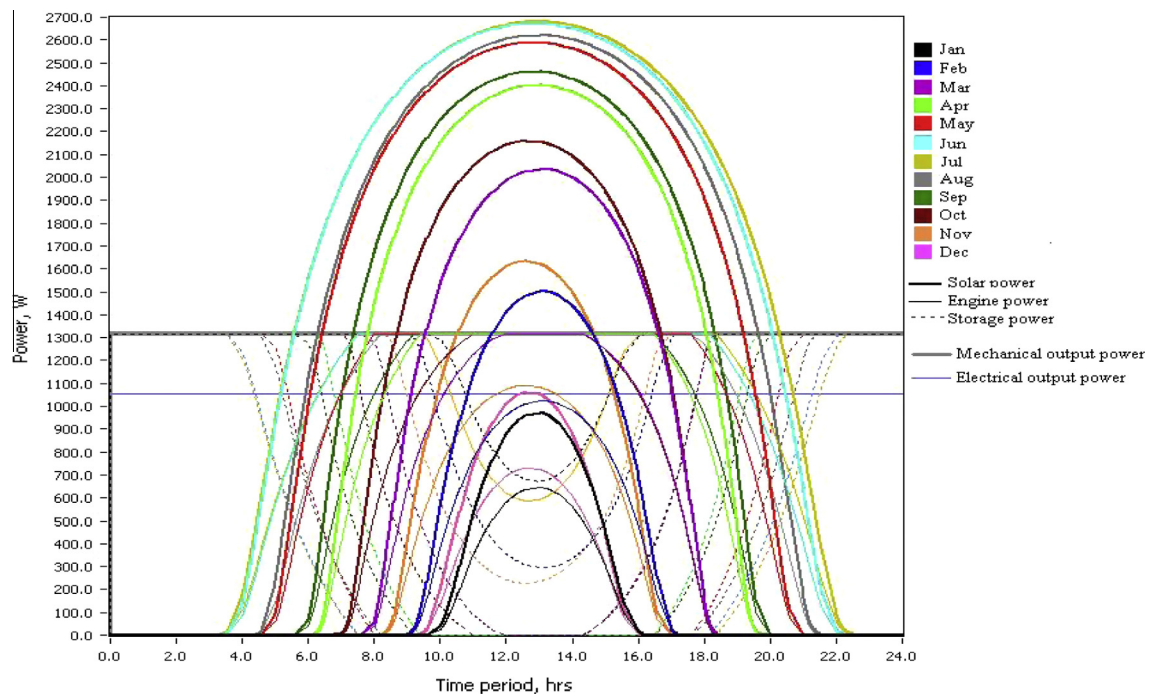


Fig. 7e. At 60° latitude.

towards the sun. So, more than half of the northern hemisphere is illuminated at any instant and maximum sunshine hour is available. The day length increases with increasing latitude till the arctic circle (66.5°N) where there is 24 h of sunlight.

Conversely, on winter solstice, the axis on the north pole tilts 23.5° away from the sun. As a result, no sunlight reaches above the arctic circle and consequently, there is darkness for 24 h. Less than half of the northern hemisphere is illuminated and experiences shortest day length.

As earth comes in its acute positions on equinoxes and solstices, these days have significant geographical values than other days of a year. So, simulation for performance assessment of the plant at different latitude has been done for these days only.

Fig. 6(a)–(d) show the daily power yield of the plant at different latitudes on equinoxes and solstices, under the solar power of those days. The solar irradiances of these days are given in Appendix A while numeric solution data has been provided in Appendix B.

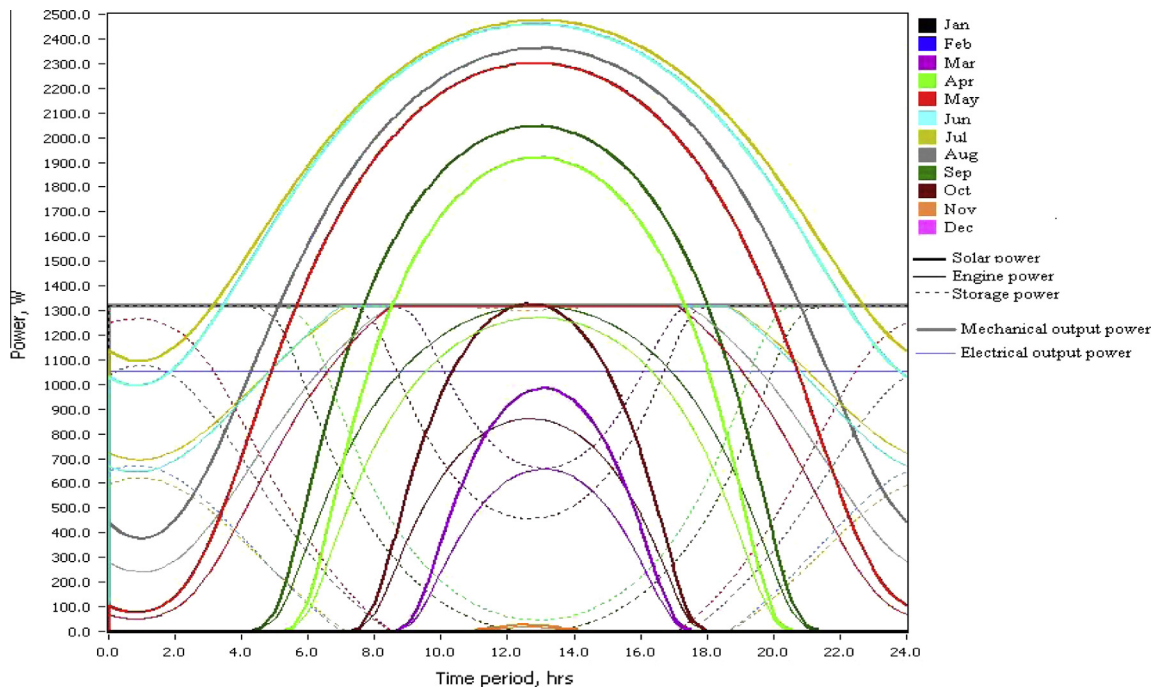


Fig. 7f. At 75° latitude.

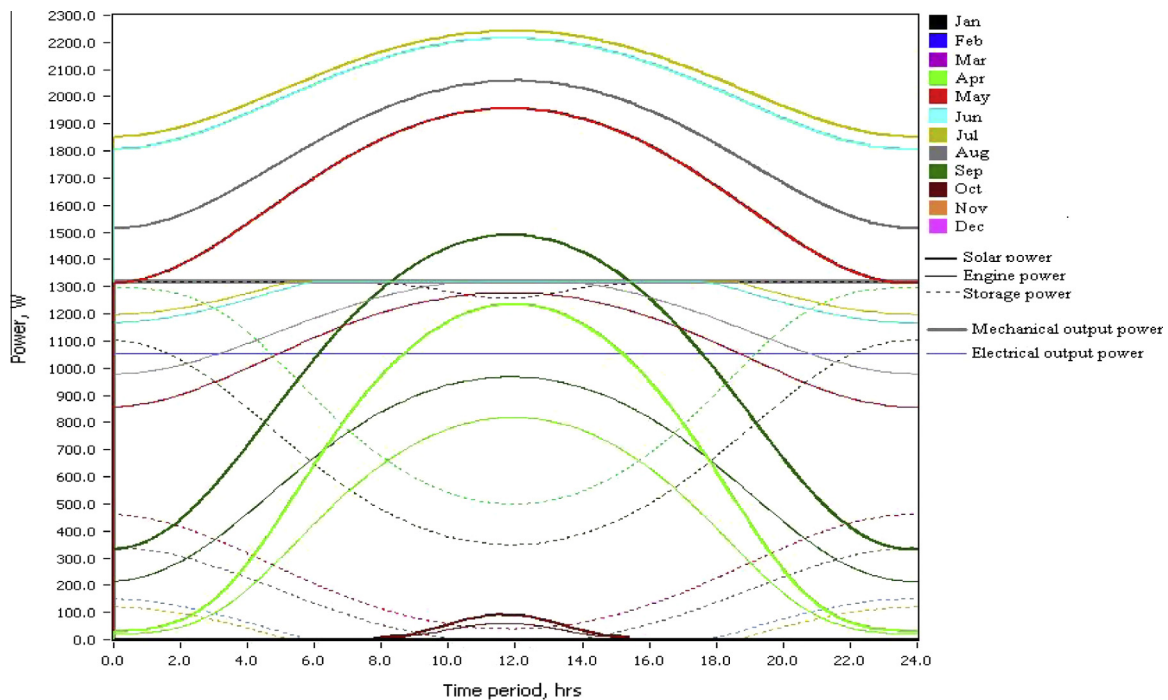


Fig. 7g. At 85° latitude.

On spring equinox (Fig. 6a) at 0–15° latitude range, the engine is driven for about 8 h solely by solar energy. But it decreases at a rate of 0.21% from 15° to 30°, 3.08% from 30° to 45° and 8.67% from 45° to 60° latitudes. Sufficient sunshine intensity is not found at latitude 75–85°, therefore, the contribution of the storage system increases with increase in latitude. Appreciable differences in results are not perceived in case of autumnal equinox (Fig. 6b) due to similar solar geometry of spring equinox and autumnal equinox.

On summer solstice (Fig. 6c), the operating hours of the plant for power generation by solar energy alone increases at a rate of 5.04% in equatorial belt, 1.21% from 15° to 30°, 3.79% from 30° to 45° latitude and so on. It is chronicled that maximum operating hours of the plant using solar energy alone is 14.02 h at 85° latitude. As, storage system is designed to compensate for the solar energy, its contribution duration decreases at an average rate of 3.30% with increase in every 15° latitude. Since, arctic circle receives solar radiation for 24 h, there is no phase for which power

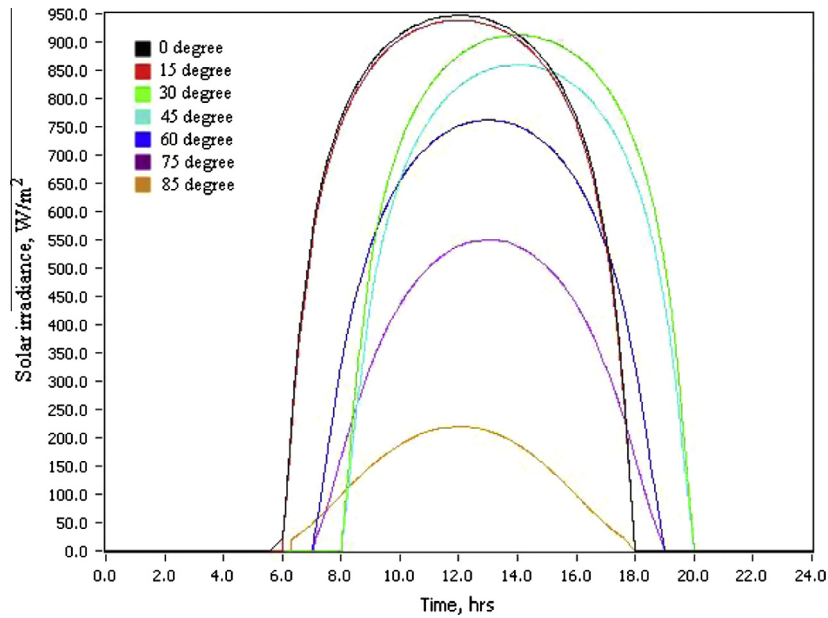


Fig. A1. Spring equinox.

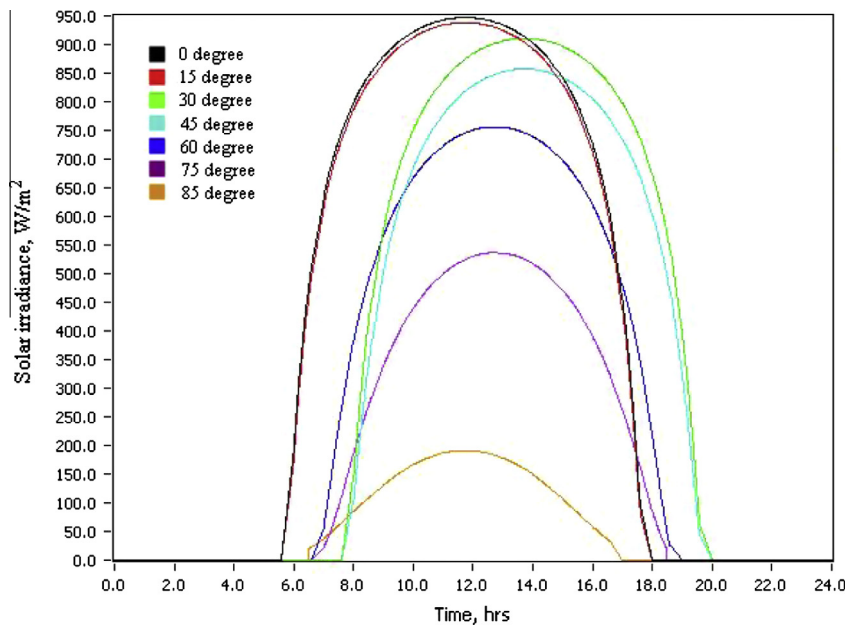


Fig. A2. Autumnal equinox.

generation completely depends on storage system. Shortest time period for which engine is operated only by solar radiation takes place in winter solstice (Fig. 6d) at latitude of 45°. Due to less reception of radiation, solar driving hour declines averagely at a rate of 11.93% and storage system contribution climbs at a rate of 5.26% for every 15° rise in latitude.

4.2. Monthly performance of the plant at different latitude

Simulation result of monthly performance of the proposed system at different latitude on 1st day of every month is shown in Fig. 7(a)–(g). The results obtained from the performance have been arranged in Appendix C.

It is observed from the results that a relatively steady sunshine duration of average 11.59 h per day is available throughout the year at latitude of 0° (Fig. 7a) and thus, duration of power generation per day from solar energy alone is noticed to have an average value of 8.47 h. Solar power and sunshine hour variations and hence, duration of energy backup go up with latitude. The storage system operates averagely at a rate of 65.67%, 64.71%, 64.47%, 71.86%, 76.89%, 84.70% and 88.76% per day in a year at latitude of 0°, 15° (Fig. 7b), 30° (Fig. 7c), 45° (Fig. 7d), 60° (Fig. 7e), 75° (Fig. 7f) and 85° (Fig. 7g) respectively. Per day maximum operating hour of storage system is 100% in the month of January, February, March, November and December at latitude of 85° and minimum is 50.91% at the latitude of 30° in the month of July. Since, size of the storage system determines the amount of storable energy; a larger

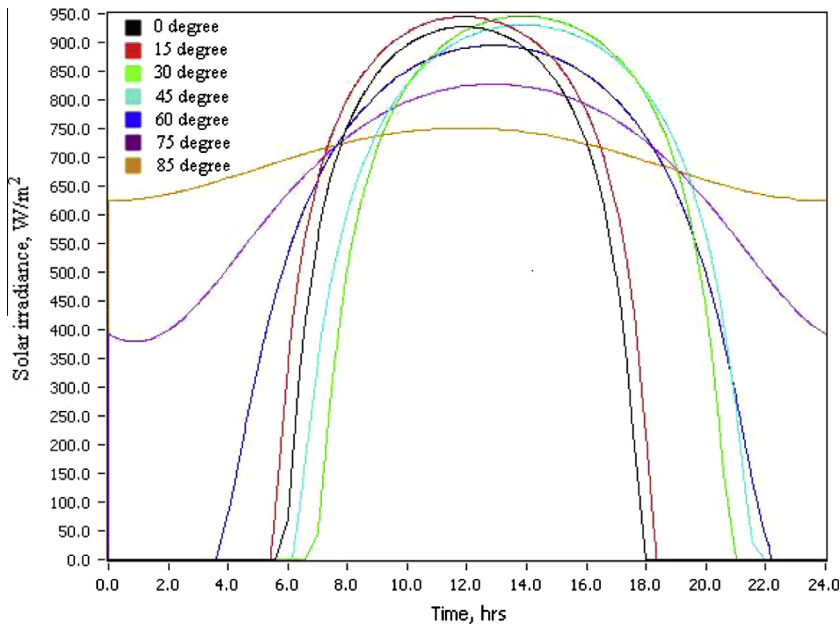


Fig. A3. Summer solstice.

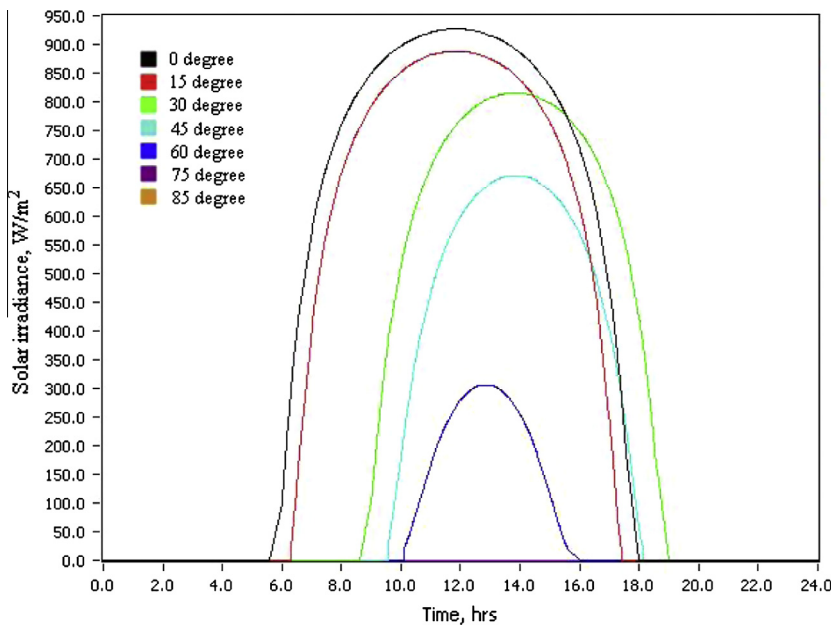


Fig. A4. Winter solstice.

system is required at latitude of 85° and eventually declines towards the equator.

5. Conclusion

This paper presents a new model and simulation of a solar-thermal power plant which is immune to the seasonal and climatic variations. The findings and conclusions are as follows.

- The proposed system is capable of generating uninterrupted constant power of 1.04 kW according to its design criteria.
- The output power is not affected by seasonal and climatic distinction and natural phenomena of day and night.
- Least fluctuation between maximum working hour (16.05 h) and minimum working hour (15.54 h) of storage system is found at latitude of 0° . Hence, inspite of minimum operating time obtained at latitude of 30° , the smallest size of the required storage system is at equatorial belt.
- Power generation from solar energy alone declines with ascending latitude. Thus, storage system plays a vital role in continuous power production at higher latitude and its dimension increases with latitude.
- Due to absence of tracking system, the proposed scheme is simpler and cost effective.
- Prominent drawbacks such as intermittency, battery autonomy, etc of the conventional solar power plants are eliminated.

Appendix A. Simulated solar irradiances on equinoxes and solstices

(See Figs. A1–A4.)

Appendix B. Summary of the latitude varying results

Day No.	Latitude (degree)	Peak solar power (W)	Sunshine duration (h)	Operation of engine (h)			Mechanical output power (kW)	Electrical output power (kW)
				Solar energy alone	Solar and stored energy	Stored energy alone		
80	0	2841.09	12.04	08.15	03.49	11.56	1.30	1.04
	15	2815.86	12.00	08.15	03.45	12.00	1.30	1.04
	30	2738.73	12.00	08.10	03.50	12.00	1.30	1.04
	45	2580.57	12.00	07.36	04.42	12.00	1.30	1.04
	60	2284.50	12.00	05.28	06.32	12.00	1.30	1.04
	75	1651.05	12.00	00.00	12.00	12.00	1.30	1.04
	85	659.76	11.56	00.00	11.56	12.04	1.30	1.04
266	0	2840.07	12.29	08.17	04.12	11.31	1.30	1.04
	15	2811.99	12.30	08.15	04.15	11.37	1.30	1.04
	30	2731.62	12.33	08.07	04.26	11.30	1.30	1.04
	45	2568.57	12.34	07.47	04.47	11.26	1.30	1.04
	60	2266.78	12.39	05.06	07.33	11.21	1.30	1.04
	75	1608.93	12.31	00.00	12.31	11.29	1.30	1.04
	85	572.28	12.15	00.00	12.15	11.55	1.30	1.04
173	0	2780.40	12.02	08.07	03.55	11.58	1.30	1.04
	15	2836.50	13.10	09.28	03.42	10.50	1.30	1.04
	30	2836.53	14.15	09.57	04.18	09.45	1.30	1.04
	45	2790.45	15.36	10.48	04.48	08.24	1.30	1.04
	60	2683.89	19.14	11.28	07.46	04.46	1.30	1.04
	75	2482.20	24.00	12.43	11.17	00.00	1.30	1.04
	85	2253.87	24.00	14.02	09.58	00.00	1.30	1.04
355	0	2780.90	12.02	08.03	03.59	11.58	1.30	1.04
	15	2640.00	10.54	07.23	03.31	13.06	1.30	1.04
	30	2445.66	10.06	06.02	04.04	13.54	1.30	1.04
	45	2013.31	08.47	01.07	07.40	15.13	1.30	1.04
	60	916.23	06.00	00.00	06.00	18.00	1.30	1.04
	75	0	00.00	00.00	00.00	24.00	1.30	1.04
	85	0	00.00	00.00	00.00	24.00	1.30	1.04

Appendix C. Numeric outcome of monthly performance at different latitude

Latitude (degree)	Month	Peak solar power (W)	Sunshine duration (h)	Operation of engine (h)			Mechanical output power (kW)	Electrical output power (kW)
				Solar energy alone	Solar and stored energy	Stored energy alone		
0	Jan	2782.80	12.04	08.05	03.59	11.56	1.30	1.04
	Feb	2806.39	12.03	08.01	04.02	11.57	1.30	1.04
	Mar	2832.53	12.00	08.06	03.54	12.00	1.30	1.04
	Apr	2834.35	11.59	08.06	03.53	12.01	1.30	1.04
	May	2808.69	12.00	07.58	04.02	12.00	1.30	1.04
	Jun	2780.02	12.00	07.56	04.04	12.00	1.30	1.04
	Jul	2777.98	11.56	07.55	04.01	12.04	1.30	1.04
	Aug	2803.58	12.01	08.02	03.59	11.59	1.30	1.04
	Sep	2828.77	12.00	08.03	03.57	12.00	1.30	1.04
	Oct	2826.81	11.58	08.02	03.56	12.02	1.30	1.04
	Nov	2799.61	11.57	08.00	03.57	12.03	1.30	1.04
	Dec	2775.76	11.59	07.56	04.03	12.01	1.30	1.04

(continued on next page)

Appendix C. (continued)

Latitude (degree)	Month	Peak solar power (W)	Sunshine duration (h)	Operation of engine (h)			Mechanical output power (kW)	Electrical output power (kW)
				Solar energy alone	Solar and stored energy	Stored energy alone		
15	Jan	2666.34	11.13	07.24	03.49	12.47	1.30	1.04
	Feb	2713.21	11.35	07.32	04.03	12.25	1.30	1.04
	Mar	2778.03	12.12	08.18	03.54	11.48	1.30	1.04
	Apr	2826.96	11.36	08.54	02.24	12.24	1.30	1.04
	May	2840.39	12.12	08.58	03.14	11.48	1.30	1.04
	Jun	2834.90	12.44	09.04	03.40	11.16	1.30	1.04
	Jul	2832.29	12.47	08.30	04.17	11.13	1.30	1.04
	Aug	2837.71	12.25	08.27	03.58	11.35	1.30	1.04
	Sep	2833.77	12.27	08.22	04.05	11.33	1.30	1.04
	Oct	2799.83	12.23	08.10	04.13	11.37	1.30	1.04
	Nov	2734.85	11.10	07.41	03.29	12.50	1.30	1.04
	Dec	2677.05	11.16	07.07	04.09	12.44	1.30	1.04
30	Jan	2454.03	10.11	05.51	04.20	13.49	1.30	1.04
	Feb	2549.59	10.02	06.23	03.39	13.58	1.30	1.04
	Mar	2670.59	11.38	07.52	03.46	12.22	1.30	1.04
	Apr	2768.52	11.54	08.03	03.51	12.06	1.30	1.04
	May	2816.59	13.21	09.37	03.44	10.39	1.30	1.04
	Jun	2833.70	13.42	09.48	03.56	10.18	1.30	1.04
	Jul	2835.88	13.50	09.52	03.58	10.01	1.30	1.04
	Aug	2825.03	13.41	11.38	02.03	10.19	1.30	1.04
	Sep	2784.11	12.17	10.34	01.43	11.43	1.30	1.04
	Oct	2702.31	11.25	07.18	04.07	12.35	1.30	1.04
	Nov	2571.13	11.16	06.38	04.38	12.44	1.30	1.04
	Dec	2466.32	10.18	06.11	04.07	13.42	1.30	1.04
45	Jan	2032.74	08.25	01.19	07.06	15.35	1.30	1.04
	Feb	2226.33	09.55	02.32	07.23	14.05	1.30	1.04
	Mar	2457.72	10.54	06.28	04.26	13.06	1.30	1.04
	Apr	2641.57	12.19	08.08	04.11	11.41	1.30	1.04
	May	2740.64	14.11	09.22	04.49	09.49	1.30	1.04
	Jun	2783.85	15.20	09.56	05.24	08.40	1.30	1.04
	Jul	2788.87	15.36	10.07	05.29	08.24	1.30	1.04
	Aug	2758.04	14.07	09.23	04.44	09.53	1.30	1.04
	Sep	2672.41	12.59	08.18	04.41	11.01	1.30	1.04
	Oct	2516.74	10.59	06.46	04.13	13.01	1.30	1.04
	Nov	2272.53	09.43	04.22	05.21	14.17	1.30	1.04
	Dec	2058.31	08.39	01.43	06.56	15.21	1.30	1.04
60	Jan	0972.28	05.59	00.00	05.59	18.01	1.30	1.04
	Feb	1301.05	07.59	00.00	07.59	16.01	1.30	1.04
	Mar	2036.39	10.14	02.26	07.48	13.46	1.30	1.04
	Apr	2402.36	13.08	07.27	05.41	10.52	1.30	1.04
	May	2588.25	15.35	09.22	06.13	08.25	1.30	1.04
	Jun	2678.01	17.58	10.51	07.07	06.02	1.30	1.04
	Jul	2680.21	17.53	10.55	06.58	06.07	1.30	1.04
	Aug	2620.55	16.06	09.24	06.42	07.54	1.30	1.04
	Sep	2461.35	13.32	07.32	06.00	10.28	1.30	1.04
	Oct	2158.15	10.53	03.02	07.51	13.07	1.30	1.04
	Nov	1623.36	08.13	00.00	08.13	15.47	1.30	1.04
	Dec	1044.54	06.08	00.00	06.08	17.52	1.30	1.04
85	Jan	0000.00	00.00	00.00	00.00	24.00	1.30	1.04
	Feb	0000.00	00.00	00.00	00.00	24.00	1.30	1.04
	Mar	0000.00	00.00	00.00	00.00	24.00	1.30	1.04
	Apr	1233.07	24.00	00.00	24.00	00.00	1.30	1.04
	May	1955.89	24.00	00.00	24.00	00.00	1.30	1.04
	Jun	2215.33	24.00	12.03	11.57	00.00	1.30	1.04
	Jul	2241.12	24.00	12.16	11.44	00.00	1.30	1.04

Appendix C. (continued)

Latitude (degree)	Month	Peak solar power (W)	Sunshine duration (h)	Operation of engine (h)			Mechanical output power (kW)	Electrical output power (kW)
				Solar energy alone	Solar and stored energy	Stored energy alone		
	Aug	2057.81	24.00	04.52	19.08	00.00	1.30	1.04
	Sep	1489.40	24.00	00.00	24.00	00.00	1.30	1.04
	Oct	0091.23	05.52	00.00	24.00	18.08	1.30	1.04
	Nov	0000.00	00.00	00.00	00.00	24.00	1.30	1.04
	Dec	0000.00	00.00	00.00	00.00	24.00	1.30	1.04

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